

Strangeness in Neutron Stars

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We discuss the role of strangeness on the internal constitution and structural properties of neutron stars. In particular, we report on recent calculations of hyperon star properties derived from microscopic equations of state for hyperonic matter. Next, we discuss the possibility of having a strange quark matter core in a neutron star, or the possible existence of strange quark matter stars, the so-called strange stars.

1. INTRODUCTION

The true nature and the internal constitutions of the ultra-dense compact stars known as neutron stars is one of the most fascinating enigma in modern astrophysics [1, 2, 3]. Different models for the equation of state (EOS) of dense matter predict the neutron star maximum mass M_{max} to be in the range $1.4 - 2.2 M_{\odot}$ ($M_{\odot} \simeq 2 \times 10^{33} \text{g}$ is the mass of the Sun), and a corresponding central density in the range of 4 – 8 times the normal saturation density ($\rho_0 \sim 2.8 \times 10^{14} \text{g/cm}^3$) of nuclear matter. Thus neutron stars are the most likely sites in the universe in which strangeness-bearing matter with a strangeness to baryon ratio $f_S = -S/B \sim 1$ may exist. Strangeness in neutron stars is expected both in a *confined* form (hyperons and or kaons), or in a *deconfined* form (strange quark matter). Accordingly different types of “neutron stars” are expected theoretically, as schematically summarized in Fig. 1.

2. NEUTRON STARS OR HYPERON STARS?

In a conservative and oversimplified picture the core of a neutron star is modeled as a uniform fluid of neutron rich nuclear matter in equilibrium with respect to the weak interactions (β -stable nuclear matter). The presence of hyperons in neutron stars was first proposed in 1960 by Ambartsumyan and Saakyan [4], and since then it has been investigated by many authors. The reason why hyperons are expected in the high dense core of a neutron star is very simple, and it is mainly a consequence of the fermionic nature of nucleons, which makes the nucleon chemical potentials a very rapidly increasing function of density. As soon as the chemical potential of neutrons becomes sufficiently large (see Fig. 2), the most energetic neutrons (*i.e.* those on the Fermi surface) can decay via the weak interactions into Λ hyperons and form a Fermi sea of this new hadronic species with $\mu_{\Lambda} = \mu_n$. The Σ^- can be produced via the weak process $e^- + n \rightarrow \Sigma^- + \nu_e$

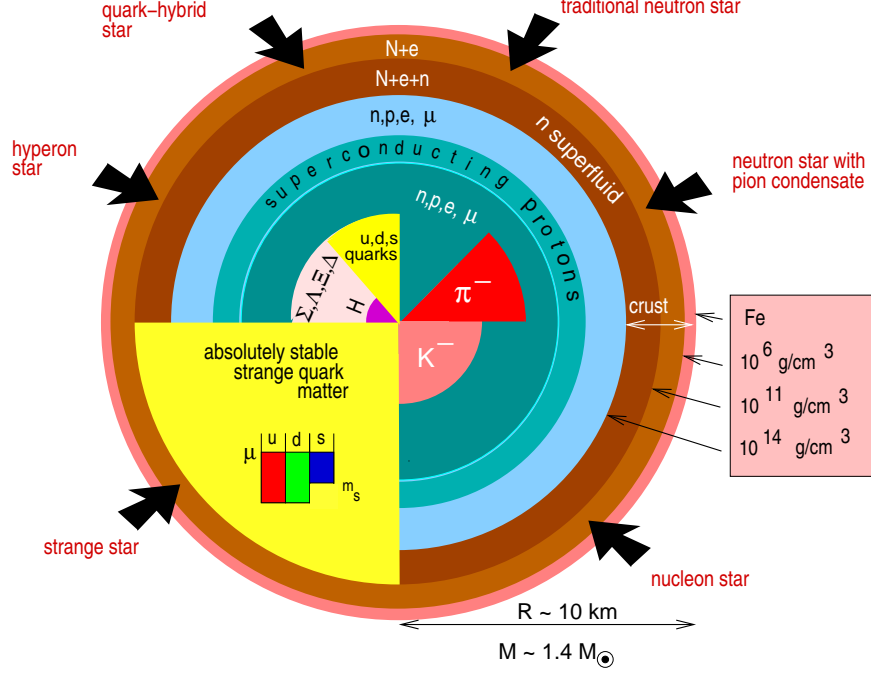


Figure 1. Schematic cross section of a neutron star according to different possibilities for the stellar constituents (adapted from ref. [2]).

when the Σ^- chemical potential fulfill the condition¹ $\mu_{\Sigma^-} = \mu_n + \mu_e$. As we can see from the results depicted in Fig. 2, hyperons appear at a relatively moderate density of about 2 times the normal saturation density ($n_0 = 0.16 \text{ fm}^{-3}$) of nuclear matter. Notice that the Σ^- hyperon appears at a lower density than the Λ , even though the Σ^- is more massive than the Λ . This is due to the contribution of the electron chemical potential μ_e to the threshold condition for the Σ^- (*i.e.* $M_{\Sigma^-} = \mu_n + \mu_e$, for free hyperons) and to the fact that μ_e in dense matter is large and can compensate for the mass difference $M_{\Sigma^-} - M_{\Lambda} = 81.76 \text{ MeV}$.

In Fig. 3, we show the profile of a such an hyperon star [6]. As we see the hyperonic matter inner core of the star extend for about 8 km. This radius has to be compared with the total stellar radius $R \sim 11 \text{ km}$, and with the thickness of the nuclear matter layer (outer core) which is about 2 km. Thus neutron stars are “giant hypernuclei” [7] under the influence of gravity and strong interactions.

The influence of hyperons on neutron stars properties has been investigated using different approaches to determine the EOS of hyperonic matter. One of the most popular approaches, to solve this problem, is the relativistic mean field model [7, 8]. Some of the

¹except from the very initial stage soon after neutron star birth, neutrinos freely escape the star and thus the neutrino chemical potentials have not to be considered in the chemical equilibrium equations.

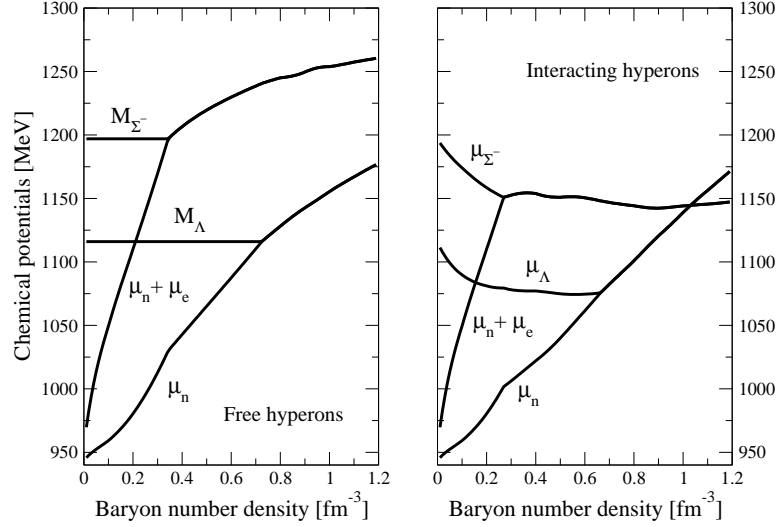


Figure 2. Chemical potentials in β -stable hyperonic matter. Left panel: free hyperons. Right panel: interacting hyperons (NSC97e interaction). Adaped from ref. [5].

parametrizations of the lagrangian of the theory have tried to reconcile measured values of neutron star masses with the binding energy of the Λ particle in hypernuclei [9, 10]. A different approach is based on the use of local effective potentials to describe the in-medium baryon-baryon (BB) interaction [11]. This method mimics and generalizes to the case of hyperonic matter the one based on the Skyrme nuclear interaction in the case of nuclear matter. Here we will report on some recent results based on a third approach, which starts from the basic BB interaction and solves the many-body problem to get the EOS for hyperonic matter. This method is based on an extension of the Brueckner-Bethe-Goldstone (BBG) theory to include hyperonic degrees of freedom [12, 13, 14, 15, 6]. In particular, the study of ref. [6] focuses on the properties of a newborn neutron star, and explores the consequences of neutrino trapping in dense matter on the structural properties and on the early evolution of neutron stars [16].

In Fig. 4, we show the EOS for β -stable dense matter (*i.e.* in equilibrium with respect to the weak interactions) obtained by Vidaña *et al.* [15] using the Nijmegen soft-core potential (NSC97e) of ref. [17] to describe the hyperon-nucleon (YN) and hyperon-hyperon (YY) interaction within the Brueckner-Hartree-Fock (BHF) approximation of the extended BBG theory. In ref. [15], the pure nucleonic contribution to the EOS has been included using a parametrization of the Akmal-Pandharipande EOS [18], where a semi-phenomenological three-nucleon (NNN) interaction of the Urbana type is added to the nuclear hamiltonian to reproduce the empirical saturation point of nuclear matter.

As expected, the presence of hyperons makes the EOS much softer with respect to the pure nucleonic case. The softening of the EOS caused by the presence of hyperons has important consequences on many macroscopic properties of the star: the maximum stellar mass is reduced by $\Delta M_{max} \sim 0.5 - 0.8 M_{\odot}$, and the corresponding central density is increased. Also, hyperon stars are more compact (*i.e.* they have a smaller radius) with

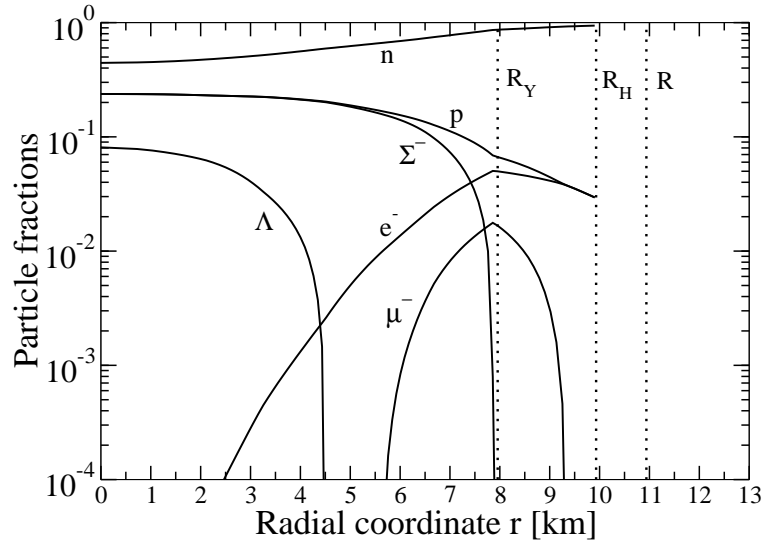


Figure 3. The internal composition of a neutron star with hyperonic matter core. The stellar baryonic mass is $M_B = 1.34 M_\odot$. R_Y is the radius of the hyperonic core. The nuclear matter layer extend between R_Y and R_H and has a thickness of about 2 km. The stellar crust extend between R_H and R and is about 1 km thick. (Adapted from Vidaña *et al.* [6]).

respect to pure nucleonic neutron stars. This is illustrated in Fig. 5, where we show the mass radius-relation for traditional neutron stars and for hyperon stars obtained with the microscopic EOS of ref. [15] (left panel) and with the relativistic mean field EOS (GM3 model) given in ref. [9]. The results depicted in Fig. 5 clearly demonstrate that to neglect hyperons leads to an overestimate of the maximum mass of neutron stars.

It is important to notice the “low” value of the stellar maximum mass, predicted within the approach of ref. [15], which is in contrast with some precise determination of neutron star masses [19]. For example in the case of the neutron star associated to the pulsar PSR1913+16, the measured stellar mass is [20]

$$M_{PSR1913+16} = (1.4411 \pm 0.0007) M_\odot . \quad (1)$$

The prediction of a value for M_{max} below the measured neutron star masses is a common feature of all the present microscopic EOS of hyperonic matter based on G-matrix BHF calculations [13, 15, 6]. For example, the authors of ref. [13], in case of the Argonne v_{18} NN interaction, found $M_{max} = 2.00 M_\odot$, a corresponding radius of $R = 10.54$ km and a central density $\rho_c = 1.11 \text{ fm}^{-3}$ for neutron stars with a pure nucleonic core. When hyperons are considered as possible stellar constituents, they found [13] $M_{max} = 1.22 M_\odot$, a corresponding radius of $R = 10.46$ km and a central density $\rho_c = 1.25 \text{ fm}^{-3}$. Therefore the current equations of state for hyperonic matter, deduced from microscopic G-matrix BHF calculations, are “too soft” to explain observed neutron star masses.

Clearly, one should try to trace the origin of this problem back to the underlying YN and YY two body interactions or to the possible repulsive three-body baryonic forces

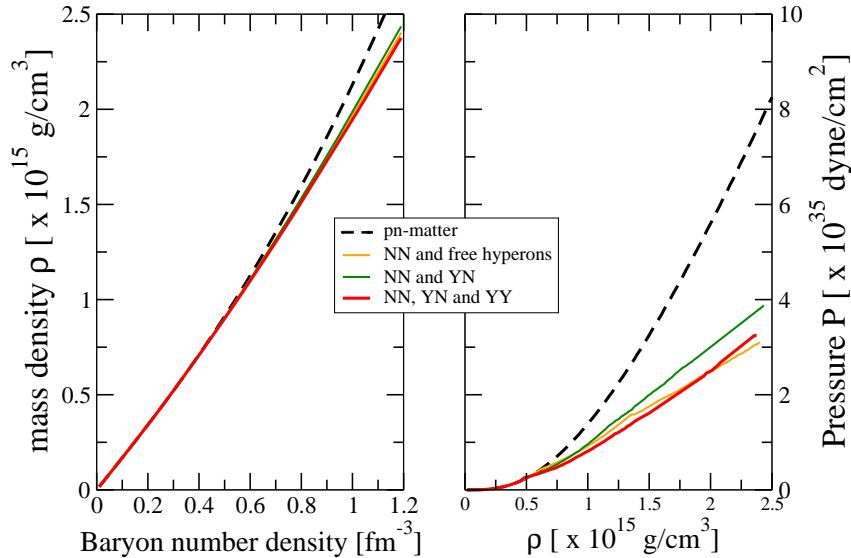


Figure 4. Equation of state of dense hadronic matter with and without hyperons [15].

involving one or more hyperons, not included in the work of ref. [12, 13, 14, 15, 6]. Presently this is a subject of very active research by people working in this field. Therefore, the use of microscopic EOSs of hyperonic matter in the contest of neutron star physics is of fundamental importance for our understanding of the strong interactions involving hyperons, and to learn how these interactions behave in dense many-body systems.

3. KAON CONDENSATION IN NEUTRON STARS

The inner core of neutron stars could also contain a Bose-Einstein condensate of negative kaons [21, 22, 23, 24, 25]. As the density of stellar matter is increased, the K^- energy is lowered by the attractive vector mean field originating from dense nucleonic matter. When the K^- energy becomes smaller than the electron chemical potential μ_e (which is an increasing function of density) the strangeness changing process $e^- \rightarrow K^- + \nu$ becomes possible. The critical density for this process has been calculated to be in the range $2.5 - 5.0 n_0$ [23, 24].

Due to the lack of space, we do not have the possibility to discuss the many relevant implications that kaon condensation has for the structure and the evolution of neutron stars. We refer the reader to the original literature on the subject (see *e.g.* [21, 22, 23, 24, 25] and references therein quoted).

4. HYBRID STARS

The core of the more massive neutron stars is one of the best candidates in the Universe where a phase transition from hadronic matter to a deconfined quark phase should occur. The quark-deconfinement phase transition proceeds through a mixed phase over a finite range of pressures and densities [26, 1]. At the onset of the mixed phase, quark matter

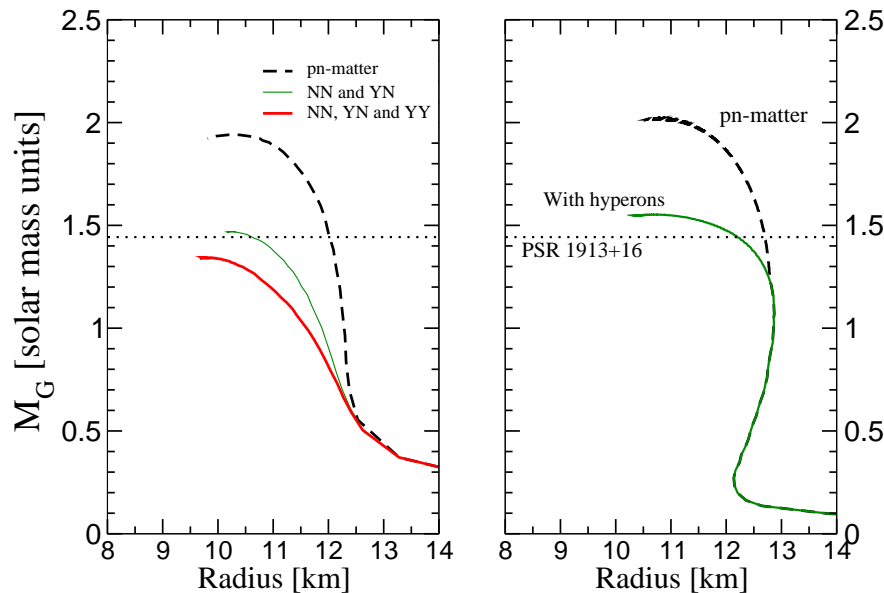


Figure 5. Mass-Radius relation for “traditional” neutron stars and hyperon stars calculated [15] within the BHF approach with the NSC9e interaction (left panel) and with the relativistic mean field EOS GM3 of ref. [9] (right panel). The dotted horizontal line indicates the measured mass for the “neutron star” in the radio pulsar PSR1913+16 .

droplets form a Coulomb lattice embedded in a sea of hadrons and in a roughly uniform sea of electrons and muons. As the pressure increases various geometrical shapes (rods, plates) of the less abundant phase immersed in the dominant one are expected. Finally the system turns into uniform quark matter at the highest pressure of the mixed phase [27]. Compact stars which possess a quark matter core, either as a mixed phase of deconfined quarks and hadrons, or as a pure quark matter phase, are called Hybrid Stars [1, 2, 3].

Many possible astrophysical signals for the appearance of a quark core in neutron stars have been proposed in the last few years (see [1, 2, 3] and references therein quoted). Particularly, pulse timing properties of pulsars have attracted much attention since they are a manifestation of the rotational properties of the associated neutron star. The onset of quark-deconfinement in the core of the star, will cause a change in the stellar moment of inertia [28]. This change will produce a peculiar evolution of the stellar rotational period ($P = 2\pi/\Omega$) which will cause large deviations of the so called pulsar braking index $n(\Omega) = (\Omega\ddot{\Omega}/\dot{\Omega}^2)$ from the *canonical* value $n = 3$, derived within the magnetic dipole model for pulsars and assuming a constant moment of inertia for the star. The possible measurement of a value of the braking index very different from the canonical value (*i.e.* $|n| \gg 3$) has been proposed [28] as a signature for the occurrence of the quark-deconfinement phase transition in a neutron star. However, it must be stressed that a large value of the braking index could also result from the pulsar magnetic field decay and/or alignment of the magnetic axis with the rotation axis [29].

5. STRANGE STARS

The possible existence of a new class of compact stars completely made of deconfined u, d, s quark matter (strange quark matter (SQM)) is one of the consequences of an hypothesis [30] formulated by A.R. Bodmer in 1971 and revived by E. Witten in 1984. These stars are usually called Strange Stars. According to the Bodmer-Witten hypothesis SQM could be the true ground state of matter. In other words, at zero temperature and pressure, the energy per baryon of SQM could be less than the energy per baryon of ^{56}Fe , which is the most tightly bound nucleus in nature. The strange matter hypothesis does not conflict with the existence of atomic nuclei as conglomerates of nucleons, or with the stability of “ordinary” matter [31, 32, 33]. Thus strange stars may exist in the universe.

One of the most likely strange star candidate is the compact object in the transient X-ray burst source SAX J1808.4-3658 (ref. [34]). This X-ray source was discovered in 1996 by the BeppoSAX satellite. Two bright type-I X-ray bursts were detected, each lasting less than 30 seconds. Analysis of the bursts in SAX J1808.4-3658 indicates that it has a peak X-ray luminosity of 6×10^{36} erg/s in its bright state, and a X-ray luminosity lower than 10^{35} erg/s in quiescence. SAX J1808.4-3658 is a X-ray *millisecond pulsar* with a pulsation period of 2.49 ms, also it is a member of a binary stellar system with orbital period of two hours. Using the observational data collected by the Rossi X-ray Timing Explorer during the the 1998 April-May outburst, Li *et al.* [34] have obtained an upper limit for the compact star radius as a function of the unknown stellar mass. Comparing this *observational* mass-radius (M-R) relation of SAX J1808.4-3658 with the theoretical M-R relations for traditional neutron stars, hyperon stars, stars with kaon condensation, and strange stars Li *et al.* [34] (see their Fig. 1) argue that a strange star model is more consistent with SAX J1808.4-3658, and suggest that it could be a strange star.

SAX J1808.4-3658 is not the only LMXBs which could harbour a strange star. Recent studies have shown that the compact stars associated with the X-ray burster 4U 1820-30 (ref.[35]), the bursting X-ray pulsar GRO J1744-28 (ref.[36]), the X-ray pulsar Her X-1 (ref.[37]), the kHz QPOs source 4U 1728-34 (ref.[38]), are likely strange star candidates. Recently, it has been suggested that the isolated compact star RX J1856.5-3754 (ref. [39]) could be a strange star.

6. QUARK-DECONFINEMENT PHASE TRANSITION IN NEUTRON STARS AND GAMMA-RAY BURSTS

Gamma Ray Bursts (GRBs) are one of the most violent and mysterious phenomena in the universe (see *e.g.* ref.[40] for a general introduction on this subject). During the last ten years two satellites, the Compton Gamma Ray Observatory (CGRO) and BeppoSAX, have revolutionized our understanding of GRBs. The Burst And Transient Source Experiment (BATSE) on board of the CGRO has demonstrated that GRBs originate at cosmological distances. The BeppoSAX discovered the X-ray afterglow. This has permitted to determine the position of some GRBs, to identify the host galaxy and, in a number of cases, to measure the red-shift. If the energy is emitted isotropically, the measured fluence of the bursts implies an energy of the order of 10^{53} erg. However, there is now compelling evidence that the γ -ray emission is not isotropic, but displays a jet-like geometry. In this case the GRB energy is of the order of 10^{51} erg [41].

Many cosmological models for the energy source of GRBs have been proposed. Presently one of the most popular is the so-called "collapsar", or "hypernova" model. Alternative models are the merging of two neutron stars (or a neutron star and a black hole) in a binary system, or the accretion of matter into a black hole. The present report is not the appropriate place to discuss the various merits and drawbacks of the many theoretical models for GRBs. In the following, we will mention some recent research which try to make a connection between GRBs and quark-deconfinement phase transition.

A possible central *engine* for GRBs is the conversion of a pure hadronic compact star to a strange star. The stellar conversion is triggered by the formation of a SQM drop in the center of the hadronic star. This idea was proposed long time ago by Alcock *et al.* [42]. Recently detailed calculations, based on different realistic models for the equation of state of neutron star matter and SQM, have been performed by the authors of ref.[43]. They showed that the total amount of energy liberated in the conversion is in the range $(1 - 4) \times 10^{53}$ erg. This energy will be mainly taken away by the neutrinos produced during the quark-deconfinement phase transition. If the efficiency of the conversion of neutrinos to γ is of the order of a few percent [44], then the birth of a strange star from a neutron star could be the energy source for GRBs.

A mounting number of observational data suggest a clear connection between supernova (SN) explosions and GRBs [45, 46, 47, 48, 49]. Particularly, in the case of the gamma ray burst of July 5, 1999 (GRB990705) and in the case of GRB011211, it has been possible to estimate the time delay between the two events. For GRB990705 the supernova explosion is evaluated to have occurred a few years before the GRB [45, 50], while for GRB011211 about four days before the burst [46].

The scenario which emerges from these findings is the following two-stage scenario: (i) the first event is the supernova explosion which forms a compact stellar remnant, *i.e.* a neutron star (NS); (ii) the second catastrophic event is associated with the NS and it is the energy source for the observed GRB. These new observational data, and the scenario outlined above, poses severe problems for most of the current theoretical models for the central energy source of GRBs. The main difficulty of all these models is to give an answer to the following questions: what is the origin of the second "explosion"? How to explain the long time delay between the two events?

In the so-called *supranova* model [51] for GRBs the second catastrophic event is the collapse to a black hole of a *supramassive* neutron star, *i.e.* a fast rotating NS with a baryonic mass M_B above the maximum baryonic mass $M_{B,max}$ for non-rotating configurations. In this model, the time delay between the SN explosion and the GRB is equal to the time needed by the fast rotating newly formed neutron star to get rid of angular momentum and to reach the limit for instability against quasi-radial modes where the collapse to a black hole occurs [52]. The supranova model needs a fine tuning in the initial spin period P_{in} and baryonic stellar mass $M_{B,in}$ to produce a supramassive neutron star that can be stabilized by rotation up to a few years. For example, if $P_{in} \geq 1.5$ ms, then the newborn supramassive neutron star must be formed within $\sim 0.03M_\odot$ above $M_{B,max}$ [52].

In a very recent paper, Berezhiani *et al.* [53] (see also ref. [54]) have proposed a new model to explain the SN-GRB association and in particular the long time delay inferred for GRB990705 and GRB011211. In the model of ref.[53], the second explosion is related

to the conversion from a metastable purely Hadronic Star (neutron star or hyperon star) into a more compact star in which deconfined quark matter is present (*i.e.* a hybrid star or a strange star). The new and crucial idea in the work of ref. [53] with respect to previous work [43], is the metastability of the hadronic star due to the existence of a non-vanishing surface tension at the interface separating hadronic matter from quark matter. The *mean-life time* of the metastable hadronic star can then be connected to the delay between the SN explosion and the GRB. The nucleation time (*i.e.* the time to form a critical-size drop of quark matter) can be extremely long if the mass of the star is small. Via mass accretion the nucleation time can be dramatically reduced and the star is finally converted from the metastable into the stable configuration [53, 54, 55]. A huge amount of energy, of the order of 10^{52} – 10^{53} erg, is released during the conversion process and can produce a powerful gamma ray burst. Within the model proposed by Berezhiani *et al.* [53] is is possible to have different time delays between the two events since the *mean-life time* of the metastable hadronic star depends on the value of the stellar central pressure. Thus the model of ref. [53] is able to interpret a time delay of a few years (as observed in GRB990705 [45, 50]), of a few days (as in the case of GRB011211 [46]), or the nearly simultaneity of the two events (as in the case of SN2003dh and GRB030329 [56]).

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